Drafting a cost-effective approach towards a sustainable manufacturing system design

Reda Ahmed O. Nujoom, Ahmed Maher Mohammed & Qian Wang

Abstract

Decision makers are being increasingly motivated to improve their manufacturing systems in coping efficiently with the objectives of sustainable development and the current manufacturing system designers or researchers face a choice to either incorporate the new regulations of sustainability into the existing systems or leave the field for new players. Consideration of sustainability aspects in developing could potentially reduce the impact of environmental wasters. Design of a sustainable manufacturing systems (SMS) can be partially achieved through the implementation of lean methods to reduce manufacturing wastes and operational costs, while improving system productivity. On the other hand, such methods of leanness does not encounter environmental wastes particularly, energy usage and carbon dioxide (CO_2) emissions of a lean manufacturing system. This work overcomes these shortcomings in developing a SMS towards the minimization of total cost, energy consumption and environmental impact, in particular, of the CO_2 emissions. The design problem was modelled as a multi-objective programming model under economic and ecological constraints. The developed model is also associated with the number of machines required for operating processes along with the quantity of flow of material for processing the products in a manufacturing system. An integrated decision-making trial and evaluation laboratory (DEMATEL)-ε-constraint approach and the goal programming approach were used to derive two sets of non-inferior solutions. Finally, a real case study was used for examining the applicability of the developed SMS model.

Keywords: Sustainability; Multi-objective optimization; DEMATEL; CO_2 emissions; lean manufacturing.

1. INTRODUCTION

To design a SMS, decision makers need to incorporate the environmentalism aspect in addition to conventional aspects in improving system efficiency and productivity (Lind *et al.,* 2008). The conventional manufacturing system configuration is normally associated with parameters of operating capacities, products flow, material-handling and production methods, operations and shop-floor layouts. However, the growing interest in environmentalism has encouraged decision makers to incorporate environmental aspects which represents an additional challenge for designers to obtain a cost-effective and environmental-friendly method (Paju *et al.,* 2010). The terms of SMS was used to refer to a compromised between the environmental and economic aspects (Taghdisian *et al.,* 2014). The manufacturing sustainability can be presented as production of manufactural goods while curtailing detrimental environmental effects relating to energy usage or depletion of natural resources. Thus, the minimization of environmental impact ought to be presented as a separate objective along with other traditional objectives such as minimizing total cost and maximizing service level and system efficiency, which form a multi-objective optimization problem.

Development of a SMS may be partially achieved by applying lean methods as a trend in modern manufacturing companies to enhance system performance adding no extra investment. Leanness can be defined as “a systematic approach to eliminate non-value added wastes in various forms and it enables continuous improvement” (Dombrowski *et al.,* 2014). These wastes are waiting for parts to arrive, overproduction, unnecessary movement of materials, unnecessary inventory, excess motion, the waste in processing and the waste of rework (Wang *et al.,* 2009). However, leanness does not encounter energy usage and CO_2 emissions in presenting a lean manufacturing system**.** (Wang *et al.,* 2009). Subsequently, it is a paramount to develop a sustainable lean manufacturing system incorporating the economic and ecological constraints as industrial factories consume energy and subsequently produce CO_2 emissions.

This paper contributes to the literature through in formulating a multi-objective model to achieve the optimal configuration of the proposed SMS design seeking a trade-off among the three objectives. The aim of objectives was to minimize the total manufacturing system cost, energy consumption due to operating machines, air-conditioning units and illumination bulbs in manufacturing processes and the CO_2 emissions released from those equipment and from the transportation vehicles. The formulated model was coded using LINGO[11] in which non-inferior solutions were obtained using an integrated DEMATEL-ε-constraint and goal programming approaches. Unlike other researches, the most important objective used to apply the ε-constraint approach is determined by using the DEMATEL algorithm which is to our knowledge a new contribution.

The rest of this article is organised as follows: Section 2 presents the literature review on sustainable manufacturing and multi-objective optimization. Section 3 describes the development of the multi-objective model. Section 4 illustrates the proposed optimization methodology. Section 5 shows an application of the developed multi-objective model and the proposed optimization methodology in a real case study and Section 6 concludes and suggests avenues for future work.

2. Literature review

There are a few studies in considering environmental aspects related to design of manufacturing systems or SMS. Heilala *et al.,* (2008) mentioned that designers of manufacturing system have to rely not just on those methods traditionally used to enhance how efficient and productive the system will be, but need to also analyze impacts that the designed system will have on the environment and surroundings. Wang *et al.,* (2008) developed an approach so-called process integration employed for examining the environmental impact for a steel company. Branham *et al.,* (2008) measured various categories of energy consumption in manufacturing system using the quantitative thermodynamic analysis. Guillen-Gosalbez and Grossmann (2009) formulated a scenario-based two objectives model employed for designing a sustainable chemical supply chain towards a minimum environmental impact.

A SMS design problem can be modelled as a multi objectives programming model towards the optimization of objectives (e.g., profits and service level). Sahar *et al.,* (2014) formulated a multiple objectives model used for minimizing CO_2 emissions of transportation and the total cost for product distribution of a dairy supply chain. Vahdani *et al.,* (2012) developed a two objectives optimization model in assisting the design of a supply chain by minimizing costs of facilities and transportation as objectives. Abdallah *et al.,* (2010) formulated a supply chain network in terms of a multiple objectives programming model aimed at minimizing environmental impact and costs. Kannan *et al.,* (2012) developed an integrated, multi echelon, multi period, multi-product optimization model used for optimizing the distribution and inventory level of a supply chain network. Zhang *et al.,* (2015) proposed a dynamical optimization method for shop-floor material handling based on real-time and multi-source manufacturing data. It integrates three important features including a new allocation strategy for move tasks, intelligent trolleys with the capability of active sensing and self-decision and the combination optimization method of move tasks to reduce the transport cost and energy. A study by Wang *et al.,* (2011) included the development of a multiple objectives model for determining a trade-off decision comparing the overall costs incurred versus the total CO_2 emitted from facilities within the supply chain. Also, as developed by Jamshidi *et al.,* (2012), a multiple objectives model was formulated considering the annual cost minimization and the effects of nitrogen dioxide, carbon monoxide and volatile organic particles caused by production at facilities and transportation in the supply chain. Niknamfar (2015) formulated a multiple objectives model optimized by using two genetic algorithms for addressing a production-distribution planning problem of a three-level supply chain. Bortolini *et al.,* (2016) formulated a multi-objective programming model to minimize operating cost, carbon footprint and delivery time in a fresh food distribution network.

To summarize, previous studies show the importance of incorporating sustainability when evaluating the performance of manufacturing system. However, there is a gap in this body of knowledge in combining lean manufacturing and environmental waste to create a balance under the economic and ecological constraints. To the best of authors' knowledge there is no study yet developed a multi objective optimization approach combining lean manufacturing and environmental impact to deal with the environmental problems as this problem still at an infant stage.

3. Developing the multi-objective model

Figure 1 shows the configuration of a SMS design in which three facilities were considered, these are supplier *s*, factory *f* and warehouse *w*. The facility (i.e., suppliers and factories) may consist of operation machines, along with air-conditioning units, bulbs and various related equipment including the compressors that supplies some of these machines with compressed air. Between facilities, there are transportation vehicles to be used. In order to achieve a SMS, energy consumption of all manufacturing equipment as well as total amount of CO_2 emissions need to be determined, along with total manufacturing system cost. The design problem was modelled as a multi-objective model to:

1. Obtain a compromised solution among the three objectives (i.e., minimum total manufacturing system cost (equation 1), energy consumption (equation 2), and CO_2 emissions (equation 3) as described below
2. Determine the optimal numbers of operation machines
3. Determine the optimal quantity of materials flows in the manufacturing system

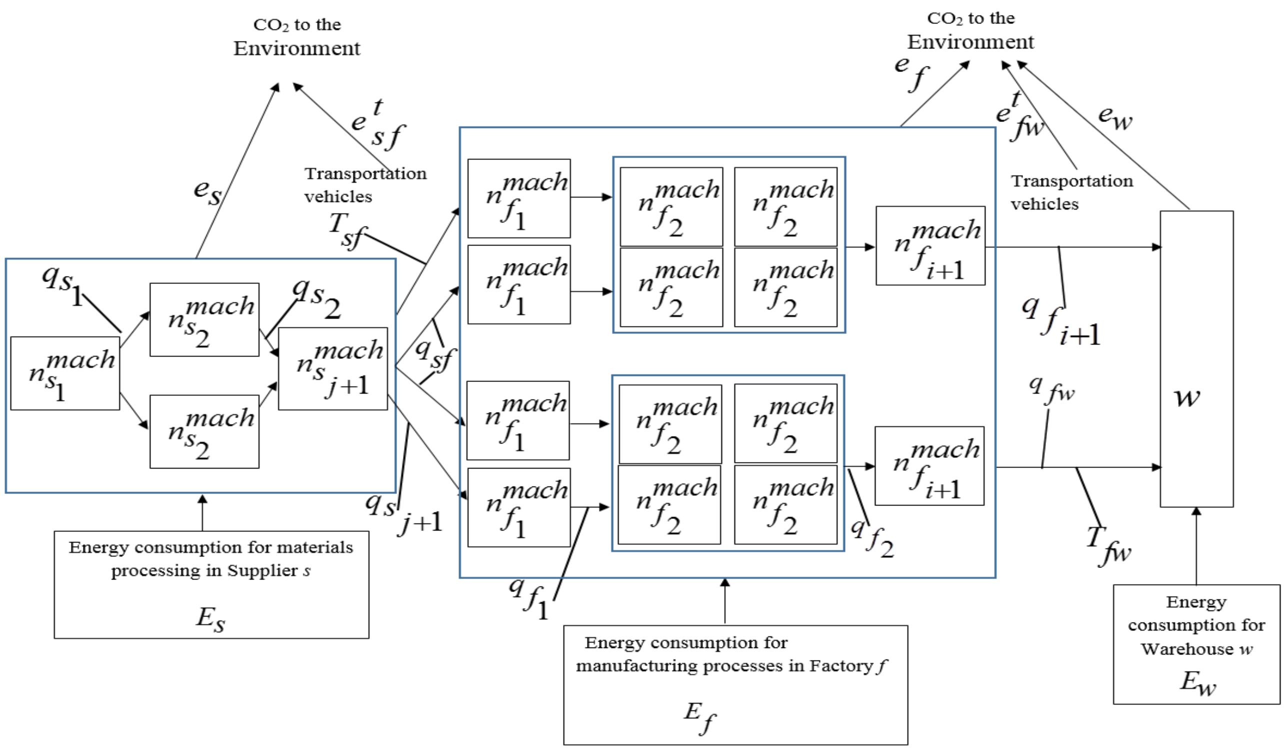


Fig.1. Configuration of the sustainable manufacturing system

Sets:

s	set of supplier s $(1\ldots s\ldots S)$
f	set of factory f $(1\ldots f\ldots F)$
w	set of warehouse $w\,(1\ldots s\ldots W)$
Π_s and Π_f	number of manufacturing processes involved in supplier s and factory f respectively.

Parameters

C_l^{es}	cost required (GBP) for establishing facility l, where $l \in \{s,\ f,\ w\}$
C_s^{mach} and C_f^{mach}	cost of machines (GBP) involved in processes j in facility s and i in facility f respectively.
C_l^{cond}	cost of an air-conditioning units (GBP) in facility l
C_l^{bulp}	cost of a lighting bulbs (GBP) in facility l
C_s^{r}	unit raw materials cost (GBP) at supplier s
C_{sf}^{r}	total raw materials cost (GBP) from supplier s to factory f
C_f^{mp}	unit manufacturing product cost (GBP) at factory f
C_{fw}^{mp}	total manufacturing product cost (GBP) from factory f to warehouse w
C_w^{I}	unit inventory cost (GBP) per product at warehouse w

C^{I}_{fw}	total inventory cost (GBP) from factory f to warehouse w
C^{t}_{l}	unit transportation cost (GBP) of transportation raw materials and product per mile between facilities l
C^{t}_{sf} and C^{t}_{fw}	total transportation cost (GBP) of raw material and products per mile from supplier s to factory f and from factory f to warehouse w respectively
T_{sf} and T_{fw}	transportation distance (miles) from supplier s to factory f and from factory f to warehouse w
Ca_{l}	operations capacity (kg) of facility l
D_{f} and D_{w}	demand (kg) of factory f and warehouse w respectively
E_{s} , E_{f} and E_{w}	energy consumption (kWh) for supplier s, for factory f and for warehouse w respectively
$E^{mach}_{s_j}$ and $E^{mach}_{f_i}$	energy consumption (kWh) for a machine in processes j in supplier s and i in factory f respectively, where $j \in \{1,\ 2,\ ....,\ \Pi_{s}\}$ and $i \in \{1,\ 2,\ ....,\ \Pi_{f}\}$
$E^{comp}_{s_j}$ and $E^{comp}_{f_i}$	energy consumption (kWh) of compressed air needed for a machine in processes j in supplier s and i in factory f respectively
$E^{cond}_{s_j}$ and $E^{cond}_{f_i}$	energy consumption (kWh) for the air-conditioning units in processes j in supplier s and i in factory f respectively

$E_{s_j}^{bulb}$ and $E_{f_i}^{bulb}$ energy consumption (kWh) for the lighting bulbs in processes *j* in supplier *s* and *i* in factory *f* respectively

E_w^{cond} and E_w^{bulb} energy consumption (kWh) for the air-conditioning units and lighting bulbs in warehouse *w* respectively

$N_{s_j}^{mach}$ and $N_{f_i}^{mach}$ installed power (kw) for a machine in processes *j* in supplier *s* and *i* in factory *f* respectively

$\Re_{s_j}$ and $\Re_{f_i}$ manufacturing rate (kg/h) for a machine in processes *j* in supplier *s* and *i* in factory *f* respectively

τ_{s_j} and τ_{f_i} operating time (hr) for a machine in processes *j* in supplier *s* and *i* in factory *f* respectively

μ_{s_j} and μ_{f_i} efficiency (%) for a machine in processes *j* in supplier *s* and *i* in factory *f* respectively

$N_{s_j}^{comp}$ and $N_{f_i}^{comp}$ installed power (kw) for a compressor in supplier *s* and factory *f* respectively

$N_{s_j}^{cond}$ and $N_{f_i}^{cond}$ installed power (kw) for an air-conditioning unit in processes *j* in supplier *s* and *i* in factory *f* respectively

$N_{s_j}^{bulb}$ and $N_{f_i}^{bulb}$ installed power (kw) for a lighting bulb in processes *j* in supplier *s* and *i* in factory *f* respectively

$\wp_s$, $\wp_f$ and $\wp_w$ mass production (kg/month) from supplier *s*, from factory *f* and stored in warehouse *w* respectively

Ψ_{s_j} and Ψ_{f_i} total waste ratio (%) for a machine involved in processes *j* in supplier *s* and *i* in factory *f* respectively

$\upsilon_{s_j}^{comp}$ and $\upsilon_{f_i}^{comp}$ compressed air (m^3/h) used for a machine in processes j in supplier s and i in factory f respectively

ρ_s^{comp} and ρ_f^{comp} capacity of a compressor (m^3/h) in supplier s and factory f respectively

$\Phi_{s_j}^{cond}$ and $\Phi_{f_i}^{cond}$ covering rate per air-conditioning unit (unit) that serves machines in processes j in supplier s and i in factory f respectively

$\varphi_{s_j}^{bulb}$ and $\varphi_{f_i}^{bulb}$ covering rate of lighting bulbs (unit) per one machine processes j in supplier and i in factory f respectively

Γ_w^{cond} covering rate per air-conditioning unit (kg) that services quantity of products in warehouse w

λ_w^{bulb} covering rate per lighting bulb (kg) that serves quantity of products in warehouse w

$e_{s_j}^{mach}$ and $e_{f_i}^{mach}$ amount of CO_2 emissions (kg) released from the machines in processes j of supplier s and i of factory f respectively

$e_{s_j}^{comp}$ and $e_{f_i}^{comp}$ amount of CO_2 emissions (kg) released from a compressor system in processes j of supplier s and i of factory f respectively

$e_{s_j}^{cond}$ and $e_{f_i}^{cond}$ amount of CO_2 emissions (kg) released from the air-conditioning units in processes j of supplier s and i of factory f respectively

$e_{s_j}^{bulb}$ and $e_{f_i}^{bulb}$ amount of CO_2 emissions (kg) released from the lighting bulbs in processes j of supplier s and i of factory f respectively

e_w^{cond} and e_w^{bulb} amount of CO_2 emissions (kg) released from air-conditioning units and the lighting bulbs involved in warehouse w respectively

e_{sf}^{t} and e_{fw}^{t} amount of CO_2 emissions (kg) released for transportation from supplier s to factory f and from factory f to warehouse w respectively

V capacity (units) per vehicle

ω_{s_j} , ω_{f_i} and ω_w CO_2 emission factor (kg/kWh) in supplier s, in factory f and warehouse w respectively

ω_{sf}^{t} and ω_{fw}^{t} CO_2 emission factor (kg/mile) released from raw material transportation from supplier s to

factory f and from products transportation from factory f to warehouse w respectively

Decision variables

$q_{s_j}^{r}$ and $q_{f_i}^{r}$ mass of material (kg) involved in processes j in supplier s and i in factory f respectively where, $j \in \{1, 2, ..., \Pi_s\}$ and $i \in \{1, 2, ..., \Pi_f\}$

$q_{s(j+1)}^{r}$ and $q_{f(i+1)}^{r}$ mass of material (kg) transferred from the machines in processes j in supplier s and i in factory f respectively

q_{sf}^{r} and q_{fw}^{mp} mass of material (kg) transported from supplier s to factory f and products transported from factory f to warehouse w

$n_{s_j}^{mach}$ and $n_{f_i}^{mach}$ number of machines (unit) in processes j in supplier s and i in factory f respectively

$n_{s_j}^{cond}$, $n_{f_i}^{cond}$ and n_w^{cond} number of air-conditioning units (unit) in processes j in supplier s and i in factory f and in warehouse w respectively

$n_{s_j}^{bulb}$, $n_{f_i}^{bulb}$ and n_{w}^{bulb} number of lighting bulbs (unit) in processes *j* in supplier *s* and *i* in factory *f* and in warehouse *w* respectively

Minimization of total cost Z_1

$$
\begin{aligned}
&Min\ Z_1 = C_s^{es} + C_f^{es} + C_w^{es} + C_s^{mach} \\
&+C_f^{mach} + C_s^{cond} + C_f^{cond} + C_w^{cond} + C_s^{bulp} \\
&+C_f^{bulp} + C_w^{bulp} + C_{sf}^{r} + C_{fw}^{mp} + C_{sf}^{t} + C_{fw}^{t} + C_{fw}^{I}
\end{aligned}
\tag{1}
$$

Where, cost required for establishing supplier *s*, factory *f* and warehouse *w* (C_s^{es}, C_f^{es} and C_w^{es}) is given respectively as follows:

$$
\begin{aligned}
&C_s^{es} = C_s^{land} + C_s^{building} \\
&+C_s^{equipment} + C_s^{services} + C_s^{saleries}
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
&C_f^{es} = C_f^{land} + C_f^{building} \\
&+C_f^{equipment} + C_f^{services} + C_f^{saleries}
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
&C_w^{es} = C_w^{land} + C_w^{building} \\
&+C_w^{equipment} + C_w^{services} + C_w^{saleries}
\end{aligned}
\tag{4}
$$

Cost of the machines C_s^{mach} and C_f^{mach} involved in process *j* at supplier *s* and in process *i* at factory *f* is given respectively as follows:

$$
C_s^{mach} = \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{mach} n_{s_j}^{machin} \right) \tag{5}
$$

$$
C_f^{mach} = \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{mach} n_{f_i}^{machin} \right) \tag{6}
$$

Cost of an air-conditioning unit C_s^{cond} , C_f^{cond} and C_w^{cond} involved in process j at supplier s, in process i at factory f and at warehouse w is determined respectively as follows:

$$C_s^{cond} = \sum_{j=1}^{\Pi_s} \left(C_{sj}^{cond} n_{sj}^{cond} \right) \tag{7}$$

$$C_f^{cond} = \sum_{j=1}^{\Pi_f} \left(C_{fi}^{cond} n_{fi}^{cond} \right) \tag{8}$$

$$C_w^{cond} = \sum_{w=1}^{W} \left(C_w^{cond} n_w^{cond} \right) \tag{9}$$

Cost of a lighting bulb C_s^{bulp} , C_f^{bulp} and C_w^{bulp} in process j at supplier s, in process i at factory f and at warehouse w is determined respectively as follows:

$$C_s^{bulp} = \sum_{j=1}^{\Pi_s} \left(C_{sj}^{bulp} n_{sj}^{bulb} \right) \tag{10}$$

$$C_f^{bulp} = \sum_{i=1}^{\Pi_f} \left(C_{fi}^{bulp} n_{fi}^{bulb} \right) \tag{11}$$

$$C_w^{bulp} = \sum_{w=1}^{W} \left(C_w^{bulp} n_w^{bulb} \right) \tag{12}$$

Total cost of raw materials at supplier s C_{sf}^{r} is calculated as below:

$$C_{sf}^{r} = \sum_{s=1}^{S} \sum_{f=1}^{F} C_s^r q_{sf}^r \tag{13}$$

Total cost of manufacturing products at factory f C_{fw}^{mp} is determined as follows:

$$C_{fw}^{mp} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_f^{mp} q_{fw}^{mp} \tag{14}$$

Total cost of transportation of raw materials per mile between s and f C_{sf}^{t} is determined as follows:

$$C_{sf}^{t} = \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^{t} \frac{q_{sf}^{r}}{V} T_{sf} \tag{15}$$

Total cost of transportation of products per mile between f and w C_{fw}^{t} is determined as follows:

$$C_{fw}^{t} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_{fw}^{t} \frac{q_{fw}^{mp}}{V} T_{fw} \tag{16}$$

Total cost of inventory C_{fw}^{I} at warehouse w is determined as follows:

$$C_{fw}^{I} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_{w}^{I} q_{fw}^{mp} \tag{17}$$

Hence, equation 1 can be expressed as follows:

$$\begin{aligned}
Min\ Z_1 = {} & C_s^{land} + C_s^{building} + C_s^{equipment} + C_s^{services} + C_s^{saleries} \\
& + C_f^{land} + C_f^{building} + C_f^{equipment} + C_f^{services} + C_f^{saleries} + C_w^{land} \\
& + C_w^{building} + C_w^{equipment} + C_w^{services} + C_w^{saleries} + \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{mach} n_{s_j}^{mach} \right) \\
& + \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{mach} n_{f_i}^{mach} \right) + \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{cond} n_{s_j}^{cond} \right) + \sum_{j=1}^{\Pi_f} \left(C_{f_i}^{cond} n_{f_i}^{cond} \right) \\
& + \sum_{w=1}^{W} \left(C_w^{cond} n_w^{cond} \right) + \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{bulp} n_{s_j}^{bulb} \right) + \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{bulp} n_{f_i}^{bulb} \right) \\
& + \sum_{w=1}^{W} \left(C_w^{bulp} n_w^{bulb} \right) + \sum_{s=1}^{S} \sum_{f=1}^{F} C_s^{r} q_{sf}^{r} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_f^{mp} q_{fw}^{mp} \\
& + \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^{t} \frac{q_{sf}^{r}}{V} T_{sf} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_{fw}^{t} \frac{q_{fw}^{mp}}{V} T_{fw} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_w^{I} q_{fw}^{mp}
\end{aligned}$$

Minimization of energy consumption Z_2

$$\begin{aligned}
Min\ Z_2 = {} & \sum_{j=1}^{\Pi_s} \left(E_{s_j}^{mach} + E_{s_j}^{cond} + E_{s_j}^{bulb} + E_{s_j}^{comp} \right) \\
& + \sum_{i=1}^{\Pi_f} \left(E_{f_i}^{mach} + E_{f_i}^{cond} + E_{f_i}^{bulb} + E_{f_i}^{comp} \right) + E_w^{cond} + E_w^{bulb}
\end{aligned} \tag{18}$$

Where,

Energy consumption $E_{s_j}^{mach}$, $E_{s_j}^{cond}$ and $E_{s_j}^{bulb}$ for machines, air-conditioning units and lighting bulbs in process *j* at supplier *s* is given respectively by:

$$E_{s_j}^{mach} = \sum_{j=1}^{\Pi_s} \left(\frac{q_{s_j}^r}{\Re_{s_j} \mu_{s_j}} N_{s_j}^{mach} n_{s_j}^{mach} \right) \tag{19}$$

$$E_{s_j}^{cond} = \sum_{j=1}^{\Pi_s} \left(N_{s_j}^{cond} n_{s_j}^{cond} \frac{q_{s(j+1)}^r}{\wp_s} \right) \tag{20}$$

$$E_{s_j}^{bulb} = \sum_{j=1}^{\Pi_s} \left(N_{s_j}^{bulb} n_{s_j}^{bulb} \frac{q_{s(j+1)}^r}{\wp_s} \right) \tag{21}$$

Energy consumption for machines in process *j* at supplier *s*, is calculated by:

$$E_{s_j}^{comp} = \sum_{j=1}^{\Pi_s} \left(\frac{q_{s_j}^r}{\Re_{s_j} \mu_{s_j}} \frac{N_{s_j}^{comp}}{\rho_{s_j}^{comp}} \upsilon_{s_j}^{comp} n_{s_j}^{mach} \right) \tag{22}$$

Energy consumption for machines, air-conditioning units and lighting bulbs in process *i* at factory *f* is determined respectively by:

$$E_{f_i}^{mach} = \sum_{i=1}^{\Pi_f} \left(\frac{q_{f_i}^r}{\Re_{f_i} \mu_{f_i}} N_{f_i}^{mach} n_{f_i}^{mach} \right) \tag{23}$$

$$E_{f_i}^{cond} = \sum_{i=1}^{\Pi_f} \left(N_{f_i}^{cond} n_{f_i}^{cond} \frac{q_{f(i+1)}^r}{\wp_f} \right) \tag{24}$$

$$E_{f_i}^{bulb} = \sum_{i=1}^{\Pi_f} \left(N_{f_i}^{bulb} n_{f_i}^{bulb} \frac{q_{f(i+1)}^r}{\wp_f} \right) \tag{25}$$

Energy consumption for machines in process i at factory f is determined as follows:

$$E_{fi}^{comp} = \sum_{i=1}^{\Pi_f}\left(\frac{q_{fi}^{r}}{\Re_{fi}\mu_{fi}}\frac{N_{fi}^{comp}}{\rho_{fi}^{comp}}\upsilon_{fi}^{comp}n_{fi}^{mach}\right) \tag{26}$$

Energy consumption for air-conditioning units and lighting bulbs at warehouse w is determined as follows:

$$E_{w}^{cond} = \sum_{w=1}^{W}\left(N_{w}^{cond}n_{w}^{cond}\frac{q_{fw}^{mp}}{\wp_w}\right) \tag{27}$$

$$E_{w}^{bulb} = \sum_{w=1}^{W}\left(N_{w}^{bulb}\times n_{w}^{bulb}\times\frac{q_{fw}^{mp}}{\wp_w}\right) \tag{28}$$

Hence, equation 18 is given as follows:

$$\begin{aligned}
Min\ \mathrm{Z}_2 = {} & \sum_{j=1}^{\Pi_s}\left(\begin{aligned}&\frac{q_{sj}^{r}}{\Re_{sj}\times\mu_{sj}}N_{sj}^{mach}n_{sj}^{mach}+N_{sj}^{cond}n_{sj}^{cond}\frac{q_{s(j+1)}^{r}}{\wp_s}+N_{sj}^{bulb}n_{sj}^{bulb}\frac{q_{s(j+1)}^{r}}{\wp_s}\\ &\frac{q_{sj}^{r}}{\Re_{sj}\times\mu_{sj}}\frac{N_{sj}^{comp}}{\rho_{sj}^{comp}}\upsilon_{sj}^{comp}n_{sj}^{mach}\end{aligned}\right)\\
& + \sum_{i=1}^{\Pi_f}\left(\begin{aligned}&\frac{q_{fi}^{r}}{\Re_{fi}\times\mu_{fi}}N_{fi}^{mach}n_{fi}^{mach}+N_{fi}^{cond}n_{fi}^{cond}\frac{q_{f(i+1)}^{r}}{\wp_f}+N_{fi}^{bulb}n_{fi}^{bulb}\frac{q_{f(i+1)}^{r}}{\wp_f}\\ &+\frac{q_{fi}^{r}}{\Re_{fi}\times\mu_{fi}}\frac{N_{fi}^{comp}}{\rho_{fi}^{comp}}\upsilon_{fi}^{comp}n_{fi}^{mach}\end{aligned}\right)\\
& + \sum_{w=1}^{W}\left(N_{w}^{cond}n_{w}^{cond}\frac{q_{w}^{mp}}{\wp_w}+N_{w}^{bulb}n_{w}^{bulb}\frac{q_{fw}^{mp}}{\wp_w}\right)
\end{aligned}$$

Minimization of CO_2 emissions Z_3

$$\begin{aligned}
Min\ \mathrm{Z}_3 = {} & \sum_{j=1}^{\Pi_s}\left[e_{sj}^{mach}+e_{sj}^{cond}+e_{sj}^{bulb}+e_{sj}^{comp}\right]+e_{sf}^{t}+e_{fw}^{t}\\
& + \sum_{i=1}^{\Pi_f}\left[e_{fi}^{mach}+e_{fi}^{cond}+e_{fi}^{bulb}+e_{fi}^{comp}\right]+e_w
\end{aligned} \tag{29}$$

Where, amount of CO_2 emissions $e_{s_j}^{mach}$, $e_{s_j}^{cond}$ and $e_{s_j}^{bulb}$ due to operating of machines, air-conditioning units and lighting bulbs in process j at supplier s is respectively determined as follows:

$$e_{s_j}^{mach} = \sum_{j=1}^{\Pi_s}\left(\omega_{s_j} \frac{q_{s_j}^{r}}{\Re_{s_j}\mu_{s_j}} N_{s_j}^{mach} n_{s_j}^{mach} \right) \tag{30}$$

$$e_{s_j}^{cond} = \sum_{j=1}^{\Pi_s}\left(0.689 N_{s_j}^{cond} n_{s_j}^{cond} \frac{q_{s(j+1)}^{r}}{\wp_s} \right) \tag{31}$$

$$e_{s_j}^{bulb} = \sum_{j=1}^{\Pi_s}\left(0.689 N_{s_j}^{bulb} n_{s_j}^{bulb} \frac{q_{s(j+1)}^{r}}{\wp_s} \right) \tag{32}$$

Amount of CO_2 emissions in process j of supplier s is determined as follows:

$$e_{s_j}^{comp} = \sum_{j=1}^{\Pi_s}\left(0.689 \frac{q_{s_j}^{r}}{\Re_{s_j}\mu_{s_j}} \frac{N_{s_j}^{comp}}{\rho_{s_j}^{comp}} \upsilon_{s_j}^{comp} n_{s_j}^{mach} \right) \quad \text{where 0.689 is the emission factor for the} \tag{33}$$

electricity

Amount of CO_2 emissions due to transporting raw material from supplier s to factory f and products from factory f to warehouse w is respectively determined as follows:

$$e_{sf}^{t} = \sum_{s=1}^{S}\sum_{f=1}^{F}\left(\omega_{sf}^{t} \frac{q_{sf}^{r}}{V} T_{sf} \right) \tag{34}$$

$$e_{fw}^{t} = \sum_{f=1}^{F}\sum_{w=1}^{W}\left(\omega_{fw}^{t} \frac{q_{fw}^{mp}}{V} T_{fw} \right) \tag{35}$$

Amount of CO_2 emissions due to operating of machines, air-conditioning units and lighting bulbs in process *i* at factory *f* is given respectively by:

$$e_{f_i}^{mach} = \sum_{i=1}^{\Pi_f} \left(\omega_{f_i} \frac{q_{f_i}^{r}}{\Re_{f_i} \mu_{f_i}} N_{f_i}^{mach} n_{f_i}^{mach} \right) \tag{36}$$

$$e_{f_i}^{cond} = \sum_{i=1}^{\Pi_f} \left(0.689 N_{f_i}^{cond} n_{f_i}^{cond} \frac{q_{f(i+1)}^{r}}{\wp_f} \right) \tag{37}$$

$$e_{f_i}^{bulb} = \sum_{i=1}^{\Pi_f} \left(0.689 N_{f_i}^{bulb} n_{f_i}^{bulb} \frac{q_{f(i+1)}^{r}}{\wp_f} \right) \tag{38}$$

Amount of CO_2 emissions $e_{f_i}^{comp}$ released from a compressor system involved in process *i* at factory *f* as below:

$$e_{f_i}^{comp} = \sum_{i=1}^{\Pi_f} \left(0.689 \frac{q_{f_i}^{r}}{\Re_{f_i} \mu_{f_i}} \frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}} \upsilon_{f_i}^{comp} n_{f_i}^{mach} \right), \text{ where 0.689 is the emission factor for the electricity} \tag{39}$$

Amount of CO_2 emissions e_W released from warehouse *w* is calculated as below:

$$e_W = 0.989 \sum_{w=1}^{W} \left(N_W^{cond} n_W^{cond} \frac{q_{fw}^{mp}}{\wp_W} + N_W^{bulb} \times n_W^{bulb} \times \frac{q_{fw}^{mp}}{\wp_W} \right) \tag{40}$$

Thus, equation 29 is given as follows:

$$Min\ Z_3 = \sum_{j=1}^{\Pi_s} \left[\begin{aligned} & \omega_{s_j} \frac{q^r_{s_j}}{\Re_{s_j} \mu_{s_j}} N^{mach}_{s_j} n^{mach}_{s_j} \\ & +0.689 \left(N^{cond}_{s_j} n^{cond}_{s_j} \frac{q^r_{s(j+1)}}{\wp_s} + N^{bulb}_{s_j} n^{bulb}_{s_j} \frac{q^r_{s(j+1)}}{\wp_s} + N^{bulb}_{s_j} n^{bulb}_{s_j} \frac{q^r_{s(j+1)}}{\wp_s} \right) \end{aligned} \right]$$

$$+ \sum_{s=1}^{S} \sum_{f=1}^{F} \left(\omega^t_{sf} \frac{q^r_{sf}}{V} T_{sf} \right) + \sum_{f=1}^{F} \sum_{w=1}^{W} \left(\omega^t_{fw} \frac{q^{mp}_{fw}}{V} T_{fw} \right)$$

$$+ \sum_{i=1}^{\Pi_f} \left[\begin{aligned} & \omega_{f_i} \frac{q^r_{f_i}}{\Re_{f_i} \mu_{f_i}} N^{mach}_{f_i} n^{mach}_{fi} \\ & +0.689 \left(N^{cond}_{fi} n^{cond}_{fi} \frac{q^r_{f(i+1)}}{\wp f} + N^{bulb}_{fi} n^{bulb}_{fi} \frac{q^r_{f(i+1)}}{\wp f} + \frac{q^r_{fi}}{\Re_{fi} \mu_{fi}} \frac{N^{comp}_{fi}}{\rho^{comp}_{fi}} \upsilon^{comp}_{fi} n^{mach}_{fi} \right) \end{aligned} \right]$$

$$+ 0.689 \sum_{w=1}^{W} \left(N^{cond}_w n^{cond}_w \frac{q^{mp}_{fw}}{\wp_w} + N^{bulb}_w \times n^{bulb}_w \times \frac{q^{mp}_{fw}}{\wp_w} \right)$$

Where, the CO_2 emission factor ω_{s_j}, ω_{f_i}, ω_w and ω^t_{sf} is listed in Table 1 (EPA, 2008); Nujoom *et al.*, 2016).

Table. 1. Amount CO_2 emission factor per kWh and Per mile

Energy source	Emission factor ω_{s_j}, ω_{f_i} and ω_w (kg/kWh)	Emission factor $\omega^t_{sf,fw}$ for truck (kg/mile)
Oil as indirect energy source to generate electricity	0.6895	0.420

3.1.Constraints

Equations 41 and 42 limit that the amount of raw material transported from supplier *s* to factory *f* and products transported from factory *f* to warehouse *w* cannot exceed their capacity.

$$q^r_{sf} \le Ca_s \tag{41}$$

$$q^{mp}_{fw} \le Ca_f \tag{42}$$

Equations 43 and 44 ensure that the demands of factory f and warehouse w are fulfilled, respectively.

$$q_{sf}^{r} \geq D_f \tag{43}$$

$$q_{fw}^{mp} \geq D_w \tag{44}$$

Equations 45 and 46 ensure that quantity of raw materials of the first process tasks j and i must be bigger

than or equal to quantity of materials of the next process task *(j+1)* and *(i+1)* in supplier s

and factory f, respectively.

$$(1-\Psi_{s_j})q_{s_j}^{r} \geq q_{s(i+1)}^{r} \tag{45}$$

$$(1-\Psi_{f_i})q_{f(i+1)}^{r} \geq q_{f(i+1)}^{r} \tag{46}$$

Equations 47 and 48 are defined in which the quantity of machines in process tasks j in supplier s and i in factory f (being served by one air-conditioning unit) is limited to be less than or equal to the quantity of air-conditioning units in this process respectively.

$$\Phi_{s_j}^{cond} n_{s_j}^{cond} \geq n_{s_j}^{mach} \tag{47}$$

$$\Phi_{f_i}^{cond} n_{f_i}^{cond} \geq n_{f_i}^{mach} \tag{48}$$

Equations 49 and 50 are defined that the number of light bulbs, which serve all the machines involved in process tasks j in supplier s and i in factory f, must be greater than or equal to the number of machines involved in this process respectively.

$$n_{s_j}^{bulb} \geq \varphi_{s_j}^{bulb} n_{s_j}^{mach} \tag{49}$$

$$n_{f_i}^{bulb} \geq \varphi_{f_i}^{bulb} n_{f_i}^{mach} \tag{50}$$

Equations 51 and 52 ensure that the quantity of products being covered using one air-conditioning unit and one lighting bulb in warehouse w, respectively.

$$\Gamma_{w}^{cond} n_{w}^{cond} \geq q_{fw}^{mp} \quad (51)$$

$$\lambda_{w}^{bulb} n_{w}^{bulb} \geq q_{fw}^{mp} \quad (52)$$

Equation 53 is a non-negativity constraint for the quantity of materials shipped from supplier *s* to factory *f* and for products shipped from factory *f* to warehouse *w*.

$$q_{s_j}^{r},\ q_{sf}^{r},\ q_{f_i}^{r},\ q_{fw}^{mp} \geq 0 \quad (53)$$

Equations 54 and 55 are defined that the manufacturing rate of process tasks *j* and *i* in supplier *s* and factory *f* must be greater than or equal to the quantity of materials involved in the next process task *(j+1)* and *(i+1)* in supplier *s* and factory *f*, respectively.

$$\Re_{s_j} n_{s_j}^{mach} \geq q_{s(i+1)}^{r} \quad (54)$$

$$\Re_{f_i} n_{f_i}^{mach} \geq q_{f(i+1)} \quad (55)$$

Where, equations 41-46 and 53 are quantity constraints; and equations 47-52, 54 and 55 are constraints in numbers of machines, air-conditioning units and lighting bulbs.

4. Optimization methodology

In this section, two optimization approaches i.e. an integrated DEMATEL-ε-constraint approach and goal programming approach were applied to reveal non-inferior solutions based on the developed three objectives optimization model. The DEMATEL algorithm was used to determine the most important objective to be kept as an objective function in implementing the ε-constraint approach. Briefly, the two approaches were utilized as described below:

4.1. ε-constraint

Based on the ε-constraint approach, the developed multi-objective model is re-presented as a mono objective model by adding constraints; the higher priority objective (i.e., total energy consumption) is considered to be an objective function (equation 56) and the other two objective functions (i.e., the total cost and the total CO_2 emissions) are moved to ε-based constraints. In this research, it is noteworthy that the DEMATEL algorithm was used to determine the most important objective to be kept as an objective function (see the next subsection 4.1.1). The solution objective function Z is expressed as follows (Chankong & Haimes, 1983):

$$Min\ Z_2 \tag{56}$$

Eq. (55) is subject to the following constrains:

$$Z_1 \leq \varepsilon_1 \tag{57}$$

$$(Z_1)^{\min} \leq \varepsilon_1 \leq (Z_1)^{\max} \tag{58}$$

$$Z_3 \leq \varepsilon_2 \tag{59}$$

$$(Z_3)^{\min} \leq \varepsilon_2 \leq (Z_3)^{\max} \tag{60}$$

And additional constraints including (equation. 41-55)

Equation 57 limits the value of the first objective to be less than or equal to ε_1 which changes between the minimum value and the maximum value for objective function one (equation 58). Equation 59 restricts the value of the third objective function to be less than or equal to ε_2 which gradually varies between the minimum value and the maximum value for objective function three (equation 60).

4.1.1. Decision-making trial and evaluation laboratory (DEMATEL)

DEMATEL is a multi-attribute decision making algorithm used to determine the weights of attributes and to examine the relationship between different variables of a complicated system. The implementation of DEMATEL includes the following steps (Tzeng *et al.,* 2007):

Step 1: Generate the linguistic evaluation decision matrix based on decision makers ‘expert. In this research the linguistic evaluation and its correspondence quantitative scale are shown in Table 2.

Step 2: Generate the quantitative pairwise compassion among the considered attribute by converting the linguistic evaluation obtained from Step 1 using the quantitative scale shown in Table 2.

$$A_{ij} = \begin{bmatrix} r_{11} & r_{12} & r_{1j} \\ r_{21} & r_{22} & r_{2j} \\ . & . & . \\ . & . & . \\ r_{i1} & r_{i2} & r_{ij} \end{bmatrix}$$

Where A_{ij} represents a pairwise decision matrix, in which the element r_{ij} denotes the level to which the ith attribute influence the jth attribute.

Step 3: After generating the pairwise decision matrix, generate the normalized direct-relation matrix N which can be generated using Eq. (61).

$$N = A.K \tag{61}$$

Where

$$K = \frac{1}{\max\limits_{1<i<n}\left(\sum\limits_{j\in n} r_{ij}\right)}; i,\ j = 1,...,n \tag{62}$$

Step 4: Generate the total-relation matrix T using Eq. 63, in which I denotes the identity matrix. The matrix T reveals the total relationship between each pair of decision attribute.

$$T = N\left(I - N\right)^{-1} \tag{63}$$

Step 5: Sum rows and columns of matrix T using Eqs. 64 and 65. These two summations are represented by D and R vectors.

$$D_i = \left[\sum_{j\in n} t_{ij}\right]_{nx1} ; i = 1, 2, ..., n \tag{64}$$

$$R_j = \left[\sum_{i\in n} t_{ij}\right]_{1xn} ; j = 1, 2, ..., n \tag{65}$$

Step 6: Define a threshold value *a*. Matrix *T* shows information on how one attribute influences another, it thus becomes required for the decision makers to define a threshold value *a* for elucidating the structural relation among attributes while simultaneously keeping the intricacy of the entire system to a convenient level. An influence relationship between two attributes is excluded from the evaluation if their correlation value in matrix *T* is smaller than *a* and only the effects greater than the set *a* value are chosen and shown in the digraph. In this work, the threshold value *a* is determined from the average of the values in matrix *T* using Eq. (66), where N is the total number of values in matrix *T*.

$$a = \frac{\sum_{i \in n} \sum_{j \in n} t_{ij}}{N} \tag{66}$$

Step 7: Build the relationship table by summing *D* and *R* and subtracting *D* from *R* in which *D*+*R* vector reveals how much importance the criterion has. The *D*-*R* vector divide the attribute into the causal and effect groups. Generally, a positive value of *D*-*R* refers to the attributes that belongs to the causal group and if a negative value *D*-*R* refers to the attributes that belongs to the effect group.

Step 8: Use Eq. 67 to determine the importance weight for each attribute by normalizing the *D*+*R* vector in which the sum of normalized weights equals to 1.

$$w_i = \frac{(D+R)_i}{\left(\sum_{i \in n} (D+R)_i\right)}; i = 1, 2, ..., n \tag{67}$$

Table. 2. Linguistic variables and correspondence scales used for evaluating the three objectives

Linguistic Variable	Scale

No influence (NI)	0
Lo influence (LI)	1
Medium influence (MI)	2
High influence (HI)	3
Very high influence (VHI)	4

4.2.Goal Programming

The purpose of the goal programming approach is to find a solution that minimizes undesirable deviations between the objective functions and their corresponding goals (Charnes *et al.*, 1955; Mohammed *et al.*, 2017). The equivalent solution formulas are presented as follows:

$$Min\ \mathrm{Z} \tag{68}$$

$$\frac{\varsigma^1}{\mathrm{G}^1} \leq Z \tag{69}$$

$$\frac{v^2}{G^2} \leq Z \tag{70}$$

$$\frac{v^3}{G^3} \leq Z \tag{71}$$

The equivalent objective functions are presented as follows.

$$
\begin{aligned}
Min\ Z_1 = {} & C_s^{land} + C_s^{building} + C_s^{equipment} + C_s^{services} + C_s^{saleries} \\
& + C_f^{land} + C_f^{building} + C_f^{equipment} + C_f^{services} + C_f^{saleries} + C_w^{land} \\
& + C_w^{building} + C_w^{equipment} + C_w^{services} + C_w^{saleries} + \sum_{j=1}^{\Pi_s}\left(C_{s_j}^{mach} n_{s_j}^{mach}\right) \\
& + \sum_{i=1}^{\Pi_f}\left(C_{f_i}^{mach} n_{f_i}^{mach}\right) + \sum_{j=1}^{\Pi_s}\left(C_{s_j}^{cond} n_{s_j}^{cond}\right) + \sum_{j=1}^{\Pi_f}\left(C_{f_i}^{cond} n_{f_i}^{cond}\right) + \sum_{w=1}^{W}\left(C_w^{cond} n_w^{cond}\right) \\
& + \sum_{j=1}^{\Pi_s}\left(C_{s_j}^{bulp} n_{s_j}^{bulb}\right) + \sum_{i=1}^{\Pi_f}\left(C_{f_i}^{bulp} n_{f_i}^{bulb}\right) + \sum_{w=1}^{W}\left(C_w^{bulp} n_w^{bulb}\right) + \sum_{s=1}^{S}\sum_{f=1}^{F} C_s^r q_{sf}^r \\
& + \sum_{f=1}^{F}\sum_{w=1}^{W} C_f^{mp} q_{fw}^{mp} + \sum_{s=1}^{S}\sum_{f=1}^{F} C_{sf}^t \frac{q_{sf}^r}{V} T_{sf} + \sum_{f=1}^{F}\sum_{w=1}^{W} C_{fw}^t \frac{q_{fw}^{mp}}{V} T_{fw} + \sum_{f=1}^{F}\sum_{w=1}^{W} C_w^I q_{fw}^{mp} + \varsigma^1 - \upsilon^1 = G^1
\end{aligned}
\tag{72}
$$

$$
\begin{aligned}
Min\ Z_2 = {} & \sum_{j=1}^{\Pi_s}\left(\begin{aligned} & \frac{q_{s_j}^r}{\Re_{s_j} \times \mu_{s_j}} N_{s_j}^{mach} n_{s_j}^{mach} + N_{s_j}^{cond} n_{s_j}^{cond} \frac{q_{s(j+1)}^r}{\wp_s} + N_{s_j}^{bulb} n_{s_j}^{bulb} \frac{q_{s(j+1)}^r}{\wp_s} \\ & \frac{q_{s_j}^r}{\Re_{s_j} \times \mu_{s_j}} \frac{N_{s_j}^{comp}}{\rho_{s_j}^{comp}} \upsilon_{s_j}^{comp} n_{s_j}^{mach} \end{aligned}\right) \\
& + \sum_{i=1}^{\Pi_f}\left(\begin{aligned} & \frac{q_{f_i}^r}{\Re_{f_i} \times \mu_{f_i}} N_{f_i}^{mach} n_{f_i}^{mach} + N_{f_i}^{cond} n_{f_i}^{cond} \frac{q_{f(i+1)}^r}{\wp_f} + N_{f_i}^{bulb} n_{f_i}^{bulb} \frac{q_{f(i+1)}^r}{\wp_f} \\ & + \frac{q_{f_i}^r}{\Re_{f_i} \times \mu_{f_i}} \frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}} \upsilon_{f_i}^{comp} n_{f_i}^{mach} \end{aligned}\right) \\
& + \sum_{w=1}^{W}\left(N_w^{cond} n_w^{cond} \frac{q_w^{mp}}{\wp_w} + N_w^{bulb} n_w^{bulb} \frac{q_{fw}^{mp}}{\wp_w}\right) + \varsigma^2 - \upsilon^2 = G^2
\end{aligned}
\tag{73}
$$

$$
\begin{aligned}
Min\ Z_3 = \sum_{j=1}^{\Pi_S} & \left[\begin{array}{l} \omega_{s_j} \dfrac{q^r_{s_j}}{\Re_{s_j}\mu_{s_j}} N^{mach}_{s_j} n^{mach}_{s_j} \\ +0.689\left(N^{cond}_{s_j} n^{cond}_{s_j} \dfrac{q^r_{s(j+1)}}{\wp_s} + N^{bulb}_{s_j} n^{bulb}_{s_j} \dfrac{q^r_{s(j+1)}}{\wp_s} + N^{bulb}_{s_j} n^{bulb}_{s_j} \dfrac{q^r_{s(j+1)}}{\wp_s} \right) \end{array} \right] \\
& + \sum_{s=1}^{S}\sum_{f=1}^{F}\left(\omega^t_{sf} \frac{q^r_{sf}}{V} T_{sf} \right) + \sum_{f=1}^{F}\sum_{w=1}^{W}\left(\omega^t_{fw} \frac{q^{mp}_{fw}}{V} T_{fw} \right) \\
+ \sum_{i=1}^{\Pi_f} & \left[\begin{array}{l} \omega_{f_i} \dfrac{q^r_{f_i}}{\Re_{f_i}\mu_{f_i}} N^{mach}_{f_i} n^{mach}_{fi} \\ +0.689\left(N^{cond}_{fi} n^{cond}_{fi} \dfrac{q^r_{f(i+1)}}{\wp_f} + N^{bulb}_{fi} n^{bulb}_{fi} \dfrac{q^r_{f(i+1)}}{\wp_f} + \dfrac{q^r_{fi}}{\Re_{fi}\mu_{fi}} \dfrac{N^{comp}_{fi}}{\rho^{comp}_{fi}} \upsilon^{comp}_{fi} n^{mach}_{fi} \right) \end{array} \right] \\
& + 0.689 \sum_{w=1}^{W}\left(N^{cond}_{w} n^{cond}_{w} \frac{q^{mp}_{fw}}{\wp_w} + N^{bulb}_{w} \times n^{bulb}_{w} \times \frac{q^{mp}_{fw}}{\wp_w} \right) + \varsigma^3 - \upsilon^3 = \mathrm{G}^3
\end{aligned}
\tag{74}
$$

Where

G^1	goal of the objective 1
G^2	goal of the objective 2
G^3	goal of the objective 3
ς^1	negative deviation variable of the objective 1
ς^2	negative deviation variable of the objective 2
ς^3	negative deviation variable of the objective 3
υ^1	positive deviation variable of the objective 1
υ^2	positive deviation variable of the objective 2
υ^3	positive deviation variable of the objective 3

Subject to an additional non-negativity restriction:

$$\varsigma, \; v \;\; \geq 0, \tag{75}$$

5. Application and evaluation: a real case study

This section presents an application of the developed multi-objective optimization model to evaluate its applicability in a real case study. The SMS includes three facilities (supplier *s*, factory *f* and warehouse *w*), and both facilities supplier *s* and factory *f* have a number of processing tasks in which each process task may has a number of machines, number of air-conditioning units and number of lighting bulbs. Each of those equipment has consumption of energy, releases an amount of CO_2 emissions and has mass inputs with different specifications. Table 3 shows the manufacturing process with the symbols representing each task of a manufacturing process for the production of plastic and woven sacks inside supplier and factory. Table 4 lists the collected data were taken from a manufacturing system which includes three facilities (1 supplier, 1 factory and 1 warehouse) used for producing plastic and woven sacks. In this case, the production line is powered by electricity which is generated using oil as indirect source of energy. The developed multi-objective optimization problem was solved using LINGO[11] software. The study was conducted by analysing the total cost for establishing these facilities, the energy consumption and the amount of CO_2 emissions towards a SMS design.

Table. 3. Processes tasks related to a plastic and woven sacks manufacturer

Tasks	Description	predecessors
A	Gas-phase	None
B	Converted the gas to liquid	A
D	Converted the liquid to powder	B
H	Converted powder to pellets	D
R.M	Raw material (polypropylene)	G
G	Extruding the Polypropylene to make stands	R.M
W	Weaving the stands into rolls of sacks	K
L	Laminating the rolls	H
P	Printing and branding	L
C	Cutting the rolls into bags	P
K	Inserts and smoothes out blown film into the bags	C
S	Blown film sewn into bag	M
Z	End product compressed	Y
W	Store the products in warehouse	Z

Tabl.4. Data related to the case study

Facilities		
Supplier *s*	Factory *f*	Warehouse *w*
C_{s}^{es} (GBP): 100000	C_{f}^{es} (GBP): 100000	C_{w}^{es} (GBP): 55000
$C_{s_j}^{mach}$ (GBP): 7000, 7000, 7000, 7000, where $j \in \{1, 2, ..., m_s\}$	$C_{f_i}^{mach}$ (GBP): 5000, 3000, 4000, 3000, 3000, 100, 200, 2000, where $i \in \{1, 2, ..., m_f\}$	-------------
$C_{s_j}^{cond}$ (GBP):1000, 1000, 1000, 1000	$C_{f_i}^{cond}$ (GBP): 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000	C_{w}^{cond} (GBP):700
$C_{s_j}^{bulp}$ (GBP): 50, 50, 50, 50	$C_{f_i}^{bulp}$ (GBP): 50, 50, 50, 50, 50, 50, 50, 50	C_{w}^{bulb} (GBP): 50
C_{s}^{r} (GBP/ kg): 2	C_{f}^{mp} (GBP/kg): 3	C_{w}^{I} (GBP/kg): 2
C_{sf}^{t} (GBP/mile): 2	C_{fw}^{t} (GBP/mile): 2	-------------
T_{sf} (mile): 50, V (kg): 20000	T_{fw} (mile): 10, V = 20000	-------------
Ca_{s} (kg/month): 1000000	Ca_{f} (kg/month): 990,000	Ca_{w} (kg/month): 900000
-------------	D_{f} (kg/month): 850000	D_{w} (kg/month): 850000
Π_{s} = 4 process	Π_{f} = 8 process	-------------
$\Re_{s_j}$ (kg/h): 1976, 1936, 1932 and 1929, where $j \in \{1, 2, ..., m_s\}$	$\Re_{f_i}$ (kg/h): 1852, 1815, 1742, 1716, 1699, 1665, 1660 and 1643, where $i \in \{1, 2, ..., m_f\}$	-------------
μ_{s_j} (%): 80 for all machines	μ_{f_i} (%): 80 for all machines	-------------
Ψ_{s_j} (%): 0.03, 0.02, 0.002, 0.15	Ψ_{f_i} (%):0.02, 0.04, 0.015, 0.01, 0.02, 0.003, 0.01, 0	-------------
$N_{s_j}^{mach}$ (kw): 700, 500, 300, 600	$N_{f_i}^{mach}$ (kw): 200, 20, 7, 40, 7, 0, 0.8, 4	-------------
$N_{s_j}^{comp}$ (kw): 0	$N_{f_i}^{comp}$ (kw): 200	-------------
$\rho_{s_j}^{comp}$ (m^3/h): 0	$\rho_{f_i}^{comp}$ (m^3/h): 666	-------------
$\upsilon_{s_j}^{comp}$ (m^3/h): 0	$\upsilon_{f_i}^{comp}$ (m^3/h): 5, 4, 13, 0, 7, 5, 20, 0, 0, 0	-------------
$N_{s_j}^{cond}$ (kw): 2.2	$N_{f_i}^{cond}$ (kw): 2.2	N_{w}^{cond} (kw): 2.2
$N_{s_j}^{bulb}$ (kw): 0.4	$N_{f_i}^{bulb}$ (kw): 0.4	N_{w}^{bulb} (kw): 0.4
$\Phi_{s_j}^{cond}$ (units): 2, $\varphi_{s_j}^{bulb}$ (units): 15	$\Phi_{f_i}^{cond}$ (units): 2, $\varphi_{f_i}^{bulb}$ (units): 15	Γ_{w}^{cond} (kg):1000, λ_{w}^{bulb} (kg): 500
$\wp_{s}$ (kg): 950000	$\wp_{f}$ (kg): 840000	$\wp_{w}$ (units): 9,032,258
ω_{s_j} (kg/kWh): 0.6895	ω_{f_i} (kg/kWh): 0.6895	ω_{w} (kg/kWh): 0.6895
ω_{sf}^{t} (kg/mile): 0.420	ω_{fw}^{t} (kg/mile): 0.420	-------------

5.1. Revealing the non-inferior solutions

Two optimization approaches (i.e., an integrated DEMATEL-ε-constraint and goal programming) were used to obtain two sets of non-inferior solutions derived from co-optimizing the three objectives in minimizing total cost Z_1, energy consumption Z_2, and CO_2 emissions Z_3. The two optimization approaches were implemented as follows:

5.1.1. ε-constraint:

As mentioned previously (see section 4.1), the most important objective has to be kept as an objective function and the other two objectives are shifted to the constraints. In view of the fact that determining the most important objective is actually an intricate multi-criteria decision making problem, thus DEMATEL algorithm was used. First, two decision makers (DM1 and DM2) from engineering and production department were invited to perform the linguistic evaluation of three objectives to generate the comparison matrix of DEMATEL and, hence, determine the importance weights of three objectives. The pairwise comparison was generated based on a 0, 1, 2, 3 and 4 scale as illustrated previously in Table 2. Table 5 shows the linguistic evaluation of the three objectives from the two decision makers 'perspective. Table 6 shows the importance weights (IW) of the three objectives in addition to *(D + R)* and *(D-R)* values. The latter values show the degree of total influence levels and the degree of net influence levels respectively, where the positive values indicate that it will influence other objectives more than any other objectives influences it. As sown in Table 6, the objective of minimizing the total energy consumption revealed the largest net influence level followed by the total cost and total CO_2 emissions, respectively. As shown in Table 6, objective of minimizing the energy consumption has the highest importance weight (0.365354387) followed by minimizing the total cost (0.338070335) and minimizing the total CO_2 emissions (0.296573326), respectively. In other words, these results proved that objective two is the most important objective based on its influence on other two objectives. Thus, the minimization of energy consumption was kept as an objective function and minimization of total cost and CO_2 emissions were shifted to the constraints. Table 7, presents the non-inferior solutions obtained by an assignment of ε-values from 20,781,782 to 26,000,000 for objective one and from 103.75×10^9 to 158.75×10^9 for objective three. It can be noted in Table 7 that the values of objective one and three are highly corresponding to the assigned values of ε_1 and ε_2 which vary between the minimum and maximum value for objectives one and three, respectively. As an example, solution 1 obtained by an assignment of ε_1=20,781,782, and ε_2 =103.75×10^9 accordingly, the minimum total manufacturing system cost is 20,500,000GBP, the minimum total energy consumption is 2,357,288 kWh and the minimum CO_2 emissions is 103748×10^{6}kg.

5.1.2. Goal programming:

The goal programming approach was implemented by assigning five different goals for the three criteria. These goals were obtained by solving the three objectives individually to obtain the ideal value. Table 8 shows the solution results obtained using the goal programming approach; this includes five non-inferior solutions. For instance, solution number 1 leads to a minimum total cost of 22,183,564 GBP, a minimum total energy consumption of 2,800,500 kWh and a minimum total CO_2 emission of 107493×10^6 kg.

Table. 5. Linguistic evaluation of the three objectives based on DM1 and DM2

Decision maker		DM1	
Objective	Cost	Energy	CO_2
C	NI	H	VH
EI	LI	NI	LI
EC	VH	VH	NI
Decision maker		DM2	
Objective	Cost	Energy	CO_2
C	NI	H	H
EI	LI	NI	MI
EC	H	VH	NI

Table. 6. Total and net influence levels and importance weights for the three objectives

Objective	D	R	D+R	D-R	Weight
C	2.7863	2.0048	4.7911	0.7814	0.338070335
EI	1.3040	2.8990	4.2030	-1.5951	0.296573326
EC	2.9957	2.1821	5.1778	0.8136	0.365354387

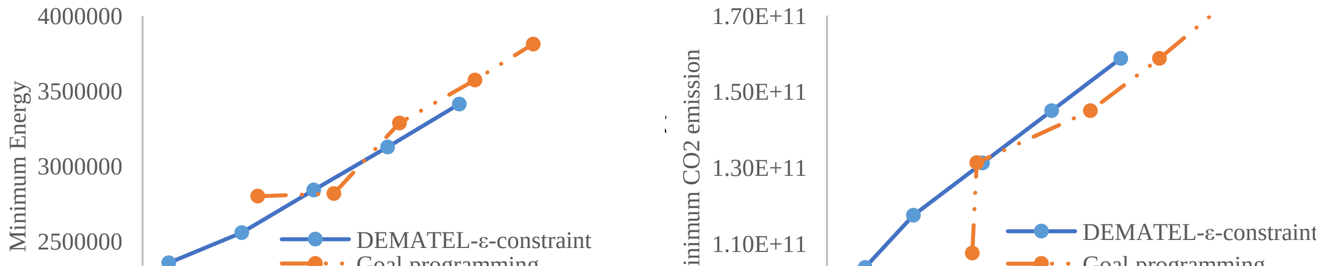
Table.7. Non-inferior solutions via the integrated DEMATEL-Ɛ-Constraint approach

Solution number	Assigned ε values		Objective function solutions		
	ε_1	ε_2	Min Z_1 (Cost) (GBP)	Min Z_2 (Energy) (kWh/month)	Min Z_3 (CO_2) (kg/month)
1	20781782	103.75×10^9	20500000	2357288	103748×10^6
2	22123925	117.5×10^9	21879729	2557194	117498×10^6
3	23466068	131.25×10^9	23239639	2842852	131248×10^6
4	24808211	145×10^9	24640700	3128510	144998×10^6
5	26000000	158.75×10^9	26000000	3414168	158748×10^6

Table 8.Non-inferior solutions via the goal programming approach.

Solution number	Objective function solutions		
	Min Z_1 (Cost) (GBP)	Min Z_2 (Energy) (kWh/month)	Min Z_3 (CO_2) (kg/month)
1	22183564	2800500	107493×10^6
2	23623925	2818500	131298×10^6
3	24867850	3287852	144948×10^6
4	26300000	3573510	158738×10^6
5	27401200	3814168	171493×10^6

Figure 2 shows Pareto fronts among the three objectives obtained via the two solution approaches. Arguably, the two approaches performed well in generating the non-inferior solutions. However, the solutions presented in Figure 2 indicates that the non-inferior solutions generated via the integrated DEMATEL-ε-constraint approach; it gives values of the total cost, total energy consumption and total CO_2 emissions less than those of the non-inferior solutions generated via the goal programing approach. For instance, the minimum manufacturing system cost under solution 1 using ε-constraint approach is 20,500,000 GBP which is less than the minimum total cost under the goal programing approach (22,183,564 GBP). Figure 2 also indicates that the non-inferior solutions generated via the integrated DEMATEL-ε-constraint approach that gives values of the total energy consumption and the total CO_2 emissions less than those of the non-inferior solutions generated via the goal programing approach. As an example, the minimum total energy consumption under solution 1 via the integrated DEMATEL-ε-constraint approach is 2,357,288 kWh which is less than the minimum total energy consumption via the goal programing approach (2,800,500 kWh) and the minimum total CO_2 emissions via the integrated DEMATEL-ε-constraint approach is 103748×10^6 kg which is less than the minimum CO_2 emissions via the goal programing approach (107493×10^6 kg). Moreover, the solutions generated via the integrated DEMATEL-ε-constraint approach are more stable compared to the solutions obtained by using the goal programming approach.



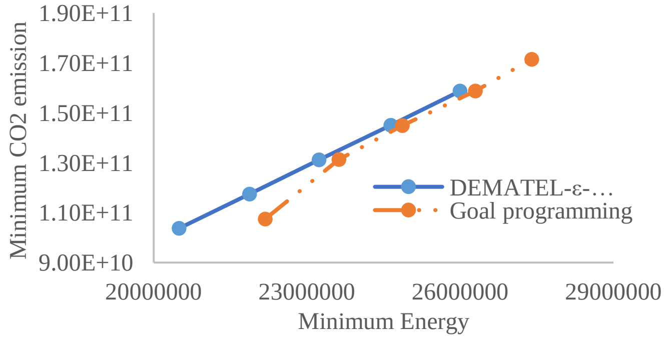


Fig.2. Pareto fronts among the three objectives using the integrated DEMATEL-ε-constraint approach and the goal programing approach

5.2. Determining the number of machines and material flows

Tables 9, 10, 11 and 12 list numbers of machines in the SMS. These solutions are associated with the non-inferior solutions generated via the integrated DEMATEL-ε-constraint approach and goal programming approach, respectively. For instance, Table 9 shows the result for solution 1 using the integrated DEMATEL-ε-constraint approach which gives the group in numbers of machines that should be involved in process task j at supplier s $n_{s_j}^{mach}$ where $j \in \{1, 2, 3, 4\}$ is (1, 1, 1, 1). Table 10 shows the result for solution 1 using the integrated DEMATEL-ε-constraint approach which gives the group in numbers of machines in process task i in factory f $n_{f_i}^{mach}$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ is (4, 32, 3, 5, 9, 9, 35, 3).

Table. 9. Number of machines related to process task j in supplier s under the integrated DEMATEL-Ɛ-constraint approach

Solution number	Numbers of machines in process j, $n_{s_j}^{mach}$ Where $j \in \{1, 2, 3, 4\}$.			
	n_{s1}	n_{s2}	n_{s3}	n_{s4}
1	1	1	1	1
2	1	1	1	1
3	2	2	1	1
4	2	2	2	1
5	2	2	1	2

Table. 10. Numbers of machines related to process task i in factory f under integrated DEMATEL-Ɛ-constraint approach

Solution number	Numbers of machines in process i, $n_{f_i}^{mach}$ Where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$.							
	n_{f1}	n_{f2}	n_{f3}	n_{f4}	n_{f5}	n_{f6}	n_{f7}	n_{f8}
1	4	32	3	5	9	9	35	3
2	4	32	3	5	10	10	40	3
3	4	40	3	5	13	13	60	4
4	5	40	4	5	14	14	60	4
5	5	45	5	6	16	16	60	5

Table 11 shows the obtained results of solution 1-5 using the goal programing approach. For instance, solution 1 gives the group (1, 2, 1, 1) in numbers of machines, which should be involved in process task j in supplier s $n_{s_j}^{mach}$ where $j \in \{1, 2, 3, 4\}$. Table 12 shows the potential group of number of machines that is in process task i in factory f $n_{f_i}^{mach}$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ is (4, 32, 3, 5, 10, 10, 36, 3) using the goal programing approach.

Table. 11. Numbers of machines related to process j in supplier s under the goal programing approach

Solution number	Numbers of machines in process j, $n_{s_j}^{mach}$ Where $j \in \{1, 2, 3, 4\}$.			
	n_{s1}	n_{s2}	n_{s3}	n_{s4}
1	1	2	1	1
2	1	2	2	1
3	2	2	1	1
4	2	2	2	1
5	2	2	1	2

Table. 12. Numbers of machines related to process *i* in factory *f* under the goal programing approach

Solution number	Numbers of machines in process i, $n_{f_i}^{mach}$ Where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$.							
	n_{f1}	n_{f2}	n_{f3}	n_{f4}	n_{f5}	n_{f6}	n_{f7}	n_{f8}
1	4	32	4	5	10	10	36	3
2	4	34	4	6	11	11	42	3
3	4	40	4	6	14	14	60	4
4	6	40	4	6	14	14	60	4
5	6	48	5	6	16	16	60	5

Figure 3a, 3b, 3c and 3d, show a comparison among potential groups in numbers of machines that should be established in the manufacturing system based on solution 1 using the integrated DEMATEL-ε-constraint approach and the goal programing approach, respectively. The results in Figure 3a and 3b indicate that the number of machines in process *j* in supplier *s* using the integrated DEMATEL-ε-constraint approach is less than the results obtained using the goal programing approach. They indicate that the number of machines needed decreases for process task 2 from 2 to 1, i.e., from (1, 2, 1, 1) to (1, 1, 1, 1). Figure 3c and 3d indicate that the number of machines in process *i* in factory *f* using the integrated DEMATEL-ε-constraint approach is less than the number obtained using the goal programing approach. They indicate that the number of machines needed decreases for process task 3 from 4 to 3, in process task 5 and 6 from 10 to 9 and in process task 7 from 36 to 35, i.e., from (4, 32, 4, 5, 10, 10, 36, 3) to (4, 32, 3, 5, 9, 9, 35, 3). Therefore, the integrated DEMATEL-ε-constraint approach is more efficient than goal programing approach for designing the SMS.

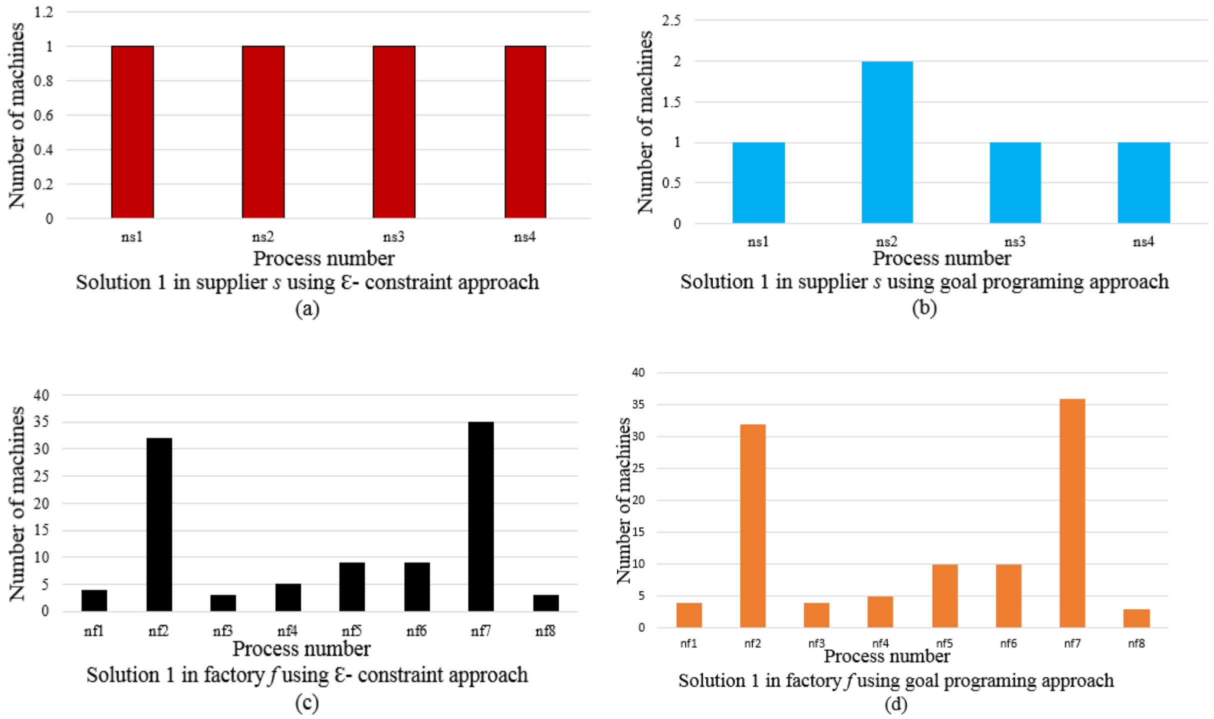


Fig.3. Comparison in numbers of machines at supplier *s* and factory *f* associate with solution 3 generated via the integrated DEMATEL-ε-constraint approach and the goal programing approach

5.3. Selecting the final solution

Next, decision makers need to select a final solution based on their experts to design the SMS. Based on the latter, solution 3 was selected as the final solution. It gives a total manufacturing system cost of (23,239,639) GBP, an energy consumption of (2,842,852) kWh and CO_2 emissions of (131248×10^6) kg. This solution includes an installation of machines that are required for operating processes task *j* at supplier *s* where, $j \in \{1, 2, 3, 4\}$ is (2, 2, 1, 1), and installation of machines that are required in processes task *i* at factory *f* where, $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ is (4, 40, 3, 5, 13, 13, 60, 4). Table 13 shows the optimal solutions in quantity of material flows (i) among the machines in process task *j* at supplier *s;* (ii) from supplier *s* to factory *f;* and (iii) among the machines in process task *i* at factory *f* and (iv) from factory *f* to warehouse *w*.

Table.13. The optimal flow of related to the raw material

Supplier s									
Solution number	q^{r}_{sj} where $j \in \{1, 2, 3, 4\}$				q^{r}_{sf}	-	-	-	-
	q_{s1}	q_{s2}	q_{s3}	q_{s4}		-	-	-	-
1	955355	950050	948100	946084	934570	-	-	-	
2	985500	965200	963040	960084	935805	-	-	-	-
3	1000000	980000	978040	976084	937040	-	-	-	-
4	1020000	1002000	996100	994084	955150	-	-	-	-
5	1045000	1027000	1009000	991100	973050	-	-	-	-
Factory f									Warehouse w
Solution number	q^{r}_{fi} where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$								q^{mp}_{fw}
	q_{f1}	q_{f2}	q_{f3}	q_{f4}	q_{f5}	q_{f6}	q_{f7}	q_{f8}	
1	934570	902423	880500	842459	830550	730100	600010	580200	6,238,709 sacks
2	935805	909227	881567	853478	842344	838459	790939	600100	6,452,688 sacks
3	937040	918299	889824	868344	850660	840467	835940	831540	8,941,290 sacks
4	955150	928300	904824	883344	865660	855467	850940	846540	9,102,580 sacks
5	973050	940200	919700	898400	883660	870500	868940	864499	9,295,688 sacks

Table 14 shows the result of solution 3 related to the numbers of machines and the quantity of materials that are required in the SMS. Figure 4 shows the optimal design of the SMS based on solution 3, which was obtained with ε_1 = 23, 466, 068, and ε_2=131.25×10^9 that yields the optimal total cost of 23,239,639 GBP, the energy consumption of 2,842,852 kWh and the CO_2 emissions of 131,248×10^6 kg.

Table.14. Numbers of machines and quantity of materials related to solution 3 see (Table 7).

The optimal solution for supplier *s*		
Process number *j*	Number of machines in process *j* $n^{mach}_{s_j}$ (units)	Quantity of materials in process *j* $q^{r}_{s_j}$ (kg)
1	2	1000000
2	2	980000
3	1	978040
4	1	976084
mass of material (kg) transported from supplier *s* to factory *f* q^{r}_{sf} (kg)		937040
The optimal solution for factory *f*		
Process number *i*	Number of machines in process *i* $n^{mach}_{f_i}$ (units)	Quantity of materials in process *i* $q^{r}_{f_i}$ (kg)
1	4	937040
2	40	918299
3	3	889824
4	5	868344
5	13	850660
6	13	840467
7	60	835940
8	4	831540
Number of manufacturing products q^{mp}_{fw} (units)		8,941,290 sacks

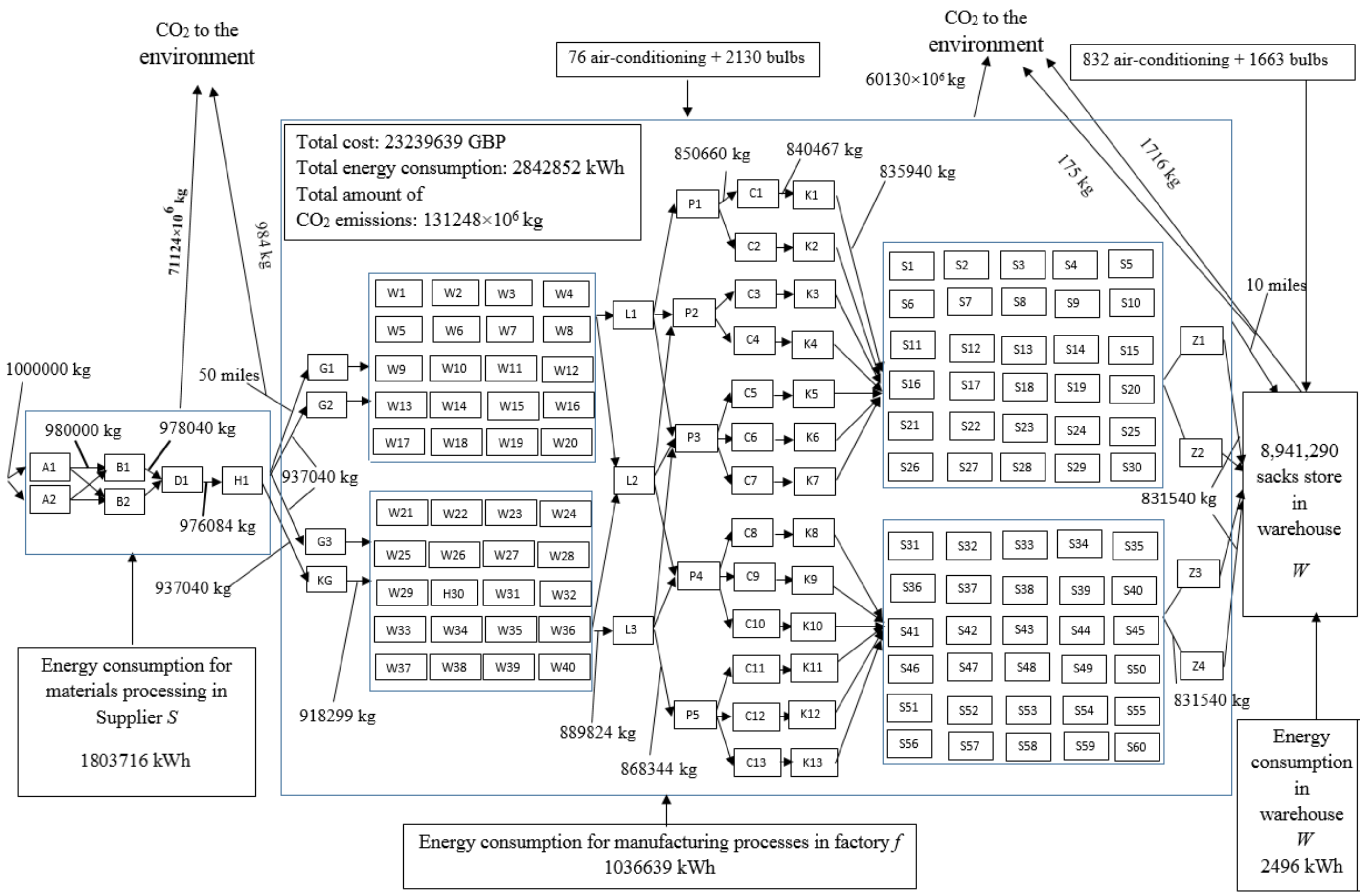


Fig.4. An optimal configuration for the sustainable manufacturing system design

6. Conclusion

Design engineers normally focus on the traditional key-factors e.g. system efficiency and operating capacity when designing a manufacturing system lacking behind the growing interest in environmental aspects. This work solves a sustainable manufacturing design problem via the formulation of a multiple objectives programming model considering economic, energy and environmental aspects. Parameters collected from a plastic and woven sacks manufacturer were used for validating the efficacy of the developed model. The study indicates that the developed multi-objective programming model can be employed as a decision-making tool used for reconfiguring the design of a conventional manufacturing system incorporating economic and ecological aspects. This research also helps decision makers in revealing a compromised solution among conflicting objectives i.e. minimization of total cost, energy consumption and environmental impacts.

Future work should focus on improving the developed model by considering a multi-period multi-objective model and formulating the social impact as an objective function when configuring the SMS.

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